

Microgating carbon nanotube field emitters by *in situ* growth inside open aperture arrays

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Multiwalled carbon nanotubes were grown using chemical vapor deposition inside small apertures having a horizontal gate and a sidewall insulator spacer. Emission currents up to 140 nA per cell at 63 V have been obtained. These arrays have exhibited a gate current as low as 2.5% of the anode current throughout the entire gate voltage range, representing the lowest gate to anode current ratio of gated nanotube emitters reported to date. We attribute this feature to the emitter geometry and method of fabrication. The overall fabrication method required only a few and simple processing steps. [DOI: 10.1063/1.1472463]

One of the first applications of carbon nanotubes (cNTs) has been their use as field emitters on account of their natural material, structural, and electronic properties which satisfy many demanding requirements for field emission, including stability, robustness, low voltage, high current-carrying capacity, and mechanical strength. A key factor to their stability as field emitters is the lack of a nonvolatile surface oxide. Surface oxide formation (such as on metal or silicon emitters) increases the work function, impedes electron transport, and makes the effective work function variable during emission. Furthermore, surface oxides could be the main cause for field emitter array (FEA) catastrophic destruction by trapping charge which could lead to arcing.¹ Carbon nanotubes are also less likely to form nanoprotusions as metal and silicon cathodes do, thus reducing the probability of current runaway.² Their small diameters (2–50 nm) and high aspect ratios enable the high electric field enhancement for low-voltage operation, despite the relatively high work function (~ 5.0 eV for graphite). They are resistant to blunting by residual back ion bombardment, especially when placed vertical to the substrate, since the nanotube diameter remains the same even when material has been removed from by sputtering.

The most commonly studied cNT emitters involved a diode configuration in which the cNTs, grown or placed as dense mats on substrates, were positioned at a known separation from an anode, to which a positive potential was applied to induce field emission from the cNTs. Although very low turn-on voltages (as low as 1–2 V per μm) were measured, the voltages used were still too high for most applications because the cNT–anode separations were usually large distances. In addition, many device applications, such as flat panel displays, require precise control of the array pixels, thus precluding a diode configuration. Hence, gating of the emission by the placement of a third electrode in close and precise proximity to a group of cNT emitters is necessary to lower the operating voltage as well as afford precise local control of emission. Gating is necessary to enable certain applications which include field emitter displays, high-

frequency amplifiers, high-voltage switches, portable x-ray sources, multibeam electron-beam lithography, radiation and temperature-insensitive electronics, space craft propulsion, and electrostatic charge management.

Gating of cNT emitters has been undertaken only within the last two years. A common technique involved the use of a cNT paste (cNTs mixed in a binding matrix) in conjunction with screen print or lithographic technology and the fabrication of “grid gates,”³ “under-gates,”^{4,5} “normal gates,”^{6–8} and “drilled gate holes.”⁹ All the gate diameters used in these studies were quite large ($>30\ \mu\text{m}$). The operating voltages for these configurations range from low to high (threshold gate voltages from 20 V to over 70 V at high anode voltages). With the exception of the work of Ito and co-workers,⁷ the gate currents were either quite high^{8,9} (over 50%) or not reported. A cNT paste technology was also used by Wang and co-workers¹⁰ in filling large gate apertures (30 μm) which had prefabricated sidewall insulator spacers. Relatively low-threshold voltages (~ 25 V) and significant gate current ($\sim 30\%$ of anode current) were observed.

To date five articles on integral microgated, *in situ* grown cNT FEAs with demonstrated emission have been published: (1) Lee and co-workers¹¹ have grown cNTs inside 0.7- μm -diam open gated apertures and have reported a low threshold voltage and the anode current-gate voltage characteristics. The gate current was not reported. (2) Talin and co-workers¹² large aperture structures produced low threshold voltages but high gate currents. (3) Perio and co-workers¹³ reported very low-threshold voltages but did not report on the gate current for their 2- μm -diam integrally gated structures. (4) Ahn and co-workers have grown cNTs inside open trenches with a buried gate,¹⁴ reported triode emission but did not show data plots. (5) Our group has grown cNTs on the tops of gated silicon posts as well as inside open gated apertures.^{15,16–17} Our cNT-on-silicon post configuration¹⁷ had a significant gate current ($\sim 30\%$ of anode current). The open gate aperture configuration, which we describe in greater detail in this letter, has the lowest reported gate current of cNT FEAs to date. The scarcity of reports on the *in situ* growth approach is largely due to the difficulty of controlling the growth of cNTs (both in length

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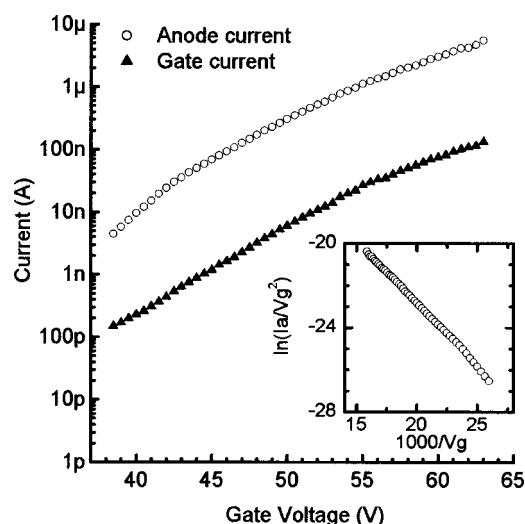


FIG. 3. Emission current-voltage characteristics from an array of 40 cells corresponding to Fig. 2. Inset shows a Fowler-Nordheim plot of the anode current.

Emission characterization was carried out in an ultra high vacuum chamber (base pressure 10^{-10} Torr) equipped with cathode, gate, and anode probes with computerized data collection for current-voltage, current-time, and electron energy distribution characteristics. The anode probe was placed about 1 mm from the arrays and an anode voltage of 200 V was used.

Figure 3 shows the current-gate voltage characteristics of the 40-cell array corresponding to Fig. 2. The threshold gate voltage was about 35 V (2 nA at 35 V), and a current of $5.6 \mu\text{A}$ was obtained at a gate voltage of 63 V. This current corresponded to about 140 nA per cell. The very low gate current (about 1/40 of the anode current) is distinctively different from all previous reports on gated cNT FEAs, which either had significant gate currents or reported only the anode currents. The inset displays a Fowler-Nordheim plot of the anode current, which suggests well-behaved field emission by its high linearity. Three of our other devices with similar template structures, with cNTs grown in three separate runs on separate days, also showed low threshold voltages V_t and low ratios of gate current to anode current I_g/I_a ($V_t=35$ V, 35 V, 45 V, and $I_g/I_a=0.04$, 0.02, and 0.06, respectively). Low gate currents are necessary for preventing gate burnout in applications that require high emission currents such as high-frequency amplifiers and high-voltage switches. For current gain ($\Delta I_a/\Delta I_g$) and power gain ($\Delta I_a \Delta V_a/\Delta I_g \Delta V_g$) devices (i.e., amplifiers), where ΔI_a , ΔI_g , ΔV_a , and ΔV_g are the changes in anode current, gate current, anode load voltage, and gate voltage, respectively, obviously a high ratio of anode current to gate current (I_a/I_g) (or a high ratio of $\Delta I_a/\Delta I_g$) is important. A high gate current can limit switching speed if the gate impedance is high so that heat generation in the gates begins to degrade the device. For field emission displays (FEDs), a significant gate to anode current ratio can be tolerated because the required emission current is low.

The single most important aspect of this letter is the combination of low gate current and low-threshold gate voltage with relatively low anode voltage (200 V at 1 mm anode-substrate separation), compared to all the other published works on gated cNT FEAs. It could possibly be attrib-

uted to the small gate diameter and a spacer thickness that was a significant fraction of the gate diameter so that any part of the gate edge could still exert significant field on all the emitting cNTs at low voltages.

In conclusion, we report the fabrication of a microgated cNT FEA, in which cNTs were grown in small diameter open apertures with insulator sidewall spacers. We believe that the most effective cNT emitters were grown on the upper portions of the spacer sidewall. We have demonstrated low-voltage and lowest gate current operation which we attributed to our unique emitter cell geometry and method of fabrication. Further emission characterization in regard to long-duration stability, effect of ambient gases, electron energy distributions, and nanotube-substrate interfaces are in progress. The manufacture of these FEAs should be very economical given the few simple processing steps.

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